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Energy-Based Closing Control Towards Contact De-bounce

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Abstract: - This paper describes the dynamic analysis of contactor system. An ac contactor is modeled and studied focusing on the problem of energy-dissipated efficiency and contact bounce during closing phase. The performance of contact bounce is characterized in terms of a set of variables, the velocity and position of movable part. Afterwards, three cost functions related to the energy dissipation of device are proposed, energy dissipation of coil resistance, energy dissipation of coil inductance, and the kinetic energy of the movable part. The aim is to understand the influence of the applied coil voltage for different initial voltage phases on the contact bounce. The best closing angle for an ac contactor is determined by comparing the kinetic energy needed for moving the movable part in each closing angle. Since the collision velocity or the moving kinetic energy of contact is decreased significantly, hence the electric life and the mechanical life of contactor can then be prolonged and the operating reliability is improved. The validation of the performance of the measurements was performed by means of simulation and experiment approach. Finally, there are some useful and valuable results are obtained and presented too.

Key-Words: - Contactor, Energy, Contact bounce, Initial phase angle, Closing phase, Movable part, Kinetic energy.

1 Introduction

In many low voltage apparatuses and power distribution systems, contactors are usually used as control switch for turning on/off power line voltage of load. In the closing phase, on the one hand the normal closing process of the contactor will circulate more current loading, the value is about six to ten time of its rated nominal current), and on the other hand there is a series of contact bounce occur between movable contact and fixed contact after the first time touched. Consequently, a harmful arc between the contacts is often possessed of high temperature lead to the contacts erosion or even welding result. The using life of contactor is then greatly decreased.

Commonly, the arc energy between movable contact and stationary contact can be characterized in term of the voltage across the normal contact, the circulating current, and the holding up time. For the purpose of reducing the amount of occasional arc energy, the holding up time of arc should be controlled as short as possible. On account of the amount of the movable-part kinetic energy is too big at the end of closing process. Therefore, there is an instantaneous impact appears between movable contact and fixed contact. Based on the basic work-energy conservation theorem in physics, the value of movable-part kinetic energy of contactor always varies with the square of its velocity value [1]. In other words, if the magnetic force which acts on the movable part can be properly controlled, the velocity or moving kinetic energy of the movable part is controlled moderately too.

There is an obvious need for an electromagnetic contactor that can close fast in many application environments. Since contact chips and cores in contactors collide in high speed, large impact forces act between the contact chips and cores. One significant problem of contactor is bouncing of the movable contacts. In order for solving the contact bounce problem, to minimize the kinetic energy prior to impact or maximize the rate of dissipation is commonly used control approaches. Nouri and Bantyukov have reported [2]-[4] that developed power electronics control approach for the reduction of contact bounce in the closing course. With the help of feedback system, the contactor can significantly reduce the kinetic energy of the contactor's movable part during its closing phase. But this solution is inexpensive; besides, the employ of this type of drive results in the extensive augment of the contactor closing time [5]. Contactors were closed at different closing phase angle of the electromagnetic coil voltage was studied by Li et al. [6]. But their study was only limited to the quantitative analysis and the best initial angle of applied ac voltage was obtained by using experimental and simulation data. On the other hand, Nouri [7] used the feedback displacement and velocity of movable part as the input variables of experience-based fuzzy controller, then output a modulated coil voltage. In contrast, Su [8] took how to get the best closing phase angle as a multi-objectives optimization problem. Unfortunately, no work has been done on the best closing angle of the ac coil voltage according to the qualitative and quantitative energy dissipation analysis in each of the contactor's subsystems. This paper aims at providing a new analytical approach; it has never been studied before. Firstly, the dynamic input electrical energy of contactor is divided into several energy dissipations in their respective subsystems for the different closing angle of applied ac voltage source. In theory, the collision energy of contact should be chosen as small as possible. Therefore, the best closing angle for an ac contactor is determined by comparing the dissipated kinetic energy for moving the movable part in each of the closing angles. Since the collision velocity or the kinetic energy of contact is the smallest at closing instant is obtained, naturally, the electrical life and mechanical life of contactor can then be prolonged and the operating reliability is improved as well.

A dynamic simulator based on the magnetic field analysis method for analyzing various behaviours of contactors with ac solenoids is proposed in this article. The simulator enables short-time analysis of dynamic motions of contactors compared with conventional simulation methods such as finite element method (FEM) [9]-[11]. To realize fast calculation of contactor model, a whole contactor system including electro-magnet circuit and mechanism are described and modelled by differential equations. The differential equations are solved simultaneously by the Runge-Kutta method.

2 Description of Contactor

The ac contactors are used to connect and disconnect many electrical systems for both power and control systems. It is composed by a set of springs and a magnetic circuit, as shown in Fig. 1. The magnetic circuit is consists of movable core, air gap, and electromagnet. By observing the contactor's mechanism, one or triple sets of electrical contacts are attached to the movable core and the movement causes the contacts to close or open depending on the strength of the magnetic force. There are two sets of springs. The first set of springs acts all the time, while the second set only acts when the movable part is close to the electromagnet. In order to obtain a smoother magnetic flux and reduce the electromagnetic noise as possible as, a set of copper shading rings are integrated with the principal coil. The magnetic effects have to be composed with the action of the principal coil.

2.1 Operation Principle of an AC Contactor

As the current in the coil is switched on, if the value of the magnetic force, which generated by the electromagnet, acts on the movable part is bigger than the springs' counter force, the movable part of electromagnet moves toward to the stable part or electromagnet until the closing phase is over. There are two time points is possible to take place contact bounce. The first time is when the movable contact touches with the stable contact, while the other time occurs when the movable core closes with the stable core.

According to the ampere right-hand laws, when the coil is applied an ac voltage, there is a magnetic flux occurs and circulates in the magnetic circuit. The value of the magnetic force acts on the movable part varies proportionally to the value of the magnetic flux or the coil current. It is known that the reluctance of the electromagnetic core generally is lower than the air-gap part. Therefore, the flux which circulates in the magnetic circuit is significantly affected by the value of air-gap reluctance [12].

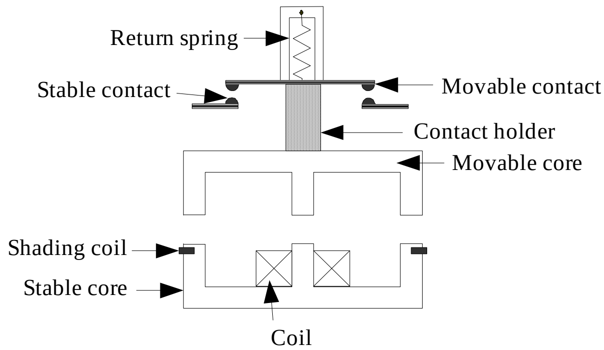


Fig. 1. Basic configuration of an ac contactor.

2.2 Mathematical Model

According to the virtual displacement principle, there is a magnetic force occurs and trends to move the movable part toward the electromagnet. When a sinusoidal source is applied to the coil and then a sinusoidal current flows the coil occur later. The value of coil current lags the applied coil voltage approximately by 90 degrees and can be expressed as

$$i(t) = I_m \sin \omega t \quad (1)$$

where I_m is the amplitude of coil current $i(t)$, ω is the power line frequency, and t is operating time. Because of the value of the magnetic flux varies with the value of coil current. The representation of magnetic flux in the magnetic circuit is given by:

$$\phi_s(t) = \phi_{mp} \sin \omega t \quad (2)$$

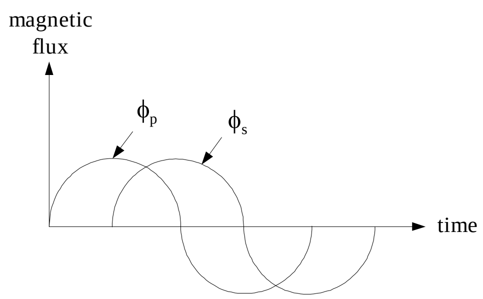
where ϕ_{mp} is the amplitude of the magnetic flux which circulates in the magnetic circuit and varies with the operating time. Equation (2) shows the magnetic flux $\phi_s(t)$, it is associated with the principal coil. Partial of the magnetic flux, $\phi_s(t)$, flows through the short-ring coil and there is a induced voltage occur to any two terminals of short-ring. Based on the Lenz's law, because of the shading ring is shorted, there is a current, which can be expressed by $\phi_{mps} \sin \omega t$, flows in the short-ring and generates a secondary magnetic flux:

$$\phi_p(t) = -\frac{\omega \phi_{mps}}{R_s} \cos \omega t \quad (3)$$

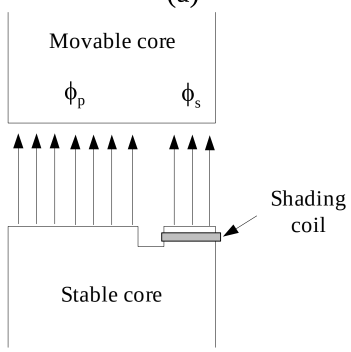
where R_s is the impedance of the shading ring. In many cases, the value of the resistance R_s is small. These parameters, $\left|\phi_p(t)\right|$, ϕ_{mp}, and ϕ_{mps} has the following relationship:

$$\left|\phi_p(t)\right| = \omega \phi_{mps} / R_s >> \phi_{mps} \quad (4)$$

$$\phi_{mps} << \phi_{mp} \quad (5)$$



(a)



(b)

Fig. 2. Magnetic flux in the magnetic circuit (a) varies with time (b) mechanical distribution.

As shown in Fig. 2, the primary and secondary magnetic flux ϕ_p and ϕ_s are plotted together. It varies with operating time. The phase angle of the secondary magnetic flux ϕ_s lagged after the primary magnetic flux ϕ_p by 90 degrees. In general, the strength of the magnetic force is proportional to the square of the value of the magnetic flux and the general expression can be written in the following forms [13]:

$$f = k\phi^2 \quad (6)$$

where

f : magnetic force which acts on the movable part,

ϕ : total magnetic flux in the magnetic circuit and it assumed that $\phi_{mp} = \phi_{ms} = \phi$ for simplicity,

k : scale factor of magnetic force.

However, although the coil is fed by a sinusoidal voltage source, there is no zero crossing point of the magnetic flux in the magnetic circuit for each cycle. Owing to the addition of shading ring, therefore the magnetic force, which acts on the movable part, is almost kept on a constant value during any dynamic process. The mechanical noise of device caused by the zero crossing point of applied ac coil voltage has been effectively controlled and the environmental quality is also improved.

3 Transient Responses Analysis

According to the respective function of contactor's subsystems, the device can be divided into electro-magnet part and mechanical part. In fact, the dynamic behaviour of contactor is an energy transition process from power to mechanical. Most of the closure time, this energy transition behaviour is a complex and non-linear [14][15]. As mentioned above, the contact bounce problem depends on the value of movable-part kinetic energy at the end of closing phase. Therefore, the dynamic behaviours of device should be observed by means of estimating the total accumulated input power energy of contactor during closing phase. In the following, the transient responses of device will be studied via two respects, namely electro-magnet part and mechanical part.

3.1 Operating Divisions

For clear explanation, the working process of contactor is divided into three sub-phases such as closing phase, closed phase, and opening phase. The profile of these sub-phases are sketched in Fig. 3 and described as follows [9][16]-[19]:

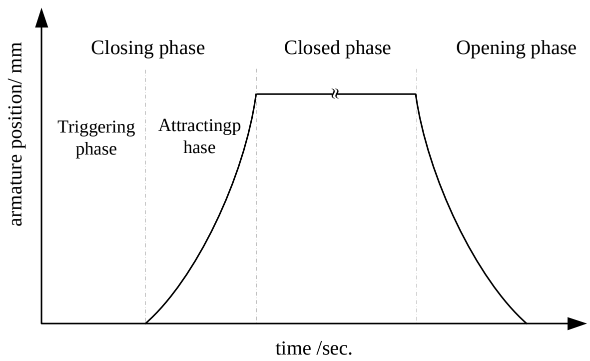


Fig. 3. Operating divisions of a contactor.

(1) Closing phase

The time period of this sub-phase is defined as the coil is energized till the air gap between movable part and electromagnet disappear. In fact, this sub-phase can be further partitioned into triggering phase and moving phase. In the triggering phase, there is no motion with the movable part. Until the moving phase begins, the magnetic force value, which acts on the movable part, is beyond the springs' counter force. Then the movable part moves forward to the electromagnet until the closing phase has finished.

(2) Closed phase

As shown in Fig. 3, the working process of close phase begins once when the movable part touched the electromagnet. In many practical cases, over distance phenomenon will take place on the movable part due to the inertia effect of the movable-part mass. In this sub-phase, because of the reluctance reduces in the magnetic circuit, the coil impedance apparently increases. Normally, the contactor need only a little input power energy to keep its contacts from dropping out.

(3) Opening phase

Provided that the applied coil voltage is absent, the magnetic force, which acts on the movable part, will immediately disappear, and then the normal contacts open and movable part moves away the electromagnet. For the sake of prolonging the using life of contactor, the allocating time of this sub-phase should be as short as possible.

3.2 Electro-magnet Part

As shown in Fig. 4, it shows the equivalent electrical circuit from the contactor's coil view point. According to the law of Kirchhoff voltage, the applied coil voltage of device should be dropped on inside each part. Respectively, the voltage drop terms occur due to the coil resistance, coil inductance, $d\lambda/dt$ (= $f_L(x,i)$), and the motion voltage, e (= $f_v(x,i)$). It is noted that the latter two terms are dependent upon the values of movable-part position x and coil current i .

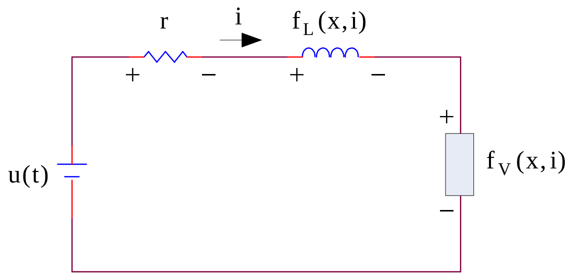


Fig. 4. Equivalent electrical circuit of a contactor.

The governing equations of an ac contactor can be represented by the following set of equations:

$$\begin{cases} u(t) = ir + \dfrac{d\lambda}{dt} + e \\ \quad = \sqrt{2}U_{RMS}\sin(wt+\varphi) \\ \dfrac{d^2x}{dt^2} = \dfrac{F_e - F_f}{m} = \dfrac{\Delta F}{m} \\ \dfrac{dx}{dt} = v \\ F_e = \dfrac{1}{2} i^2 \dfrac{dL}{dx} \end{cases} \tag{7}$$

where the symbols are respectively defined as follows:

u : coil voltage,
r : coil resistance,
m : mass of movable part,
w : angular frequency of ac applied coil voltage,
t : operating time,
φ : initial phase angle of ac applied voltage source,
F_f : counter force, which is produced by the spring system,
F_e : magnetic force, which is produced by the electromagnet,
λ : flux linkage of coil, it can be expressed by coil inductance and coil current or the number of coil turns and magnetic flux,

$$\lambda = L(x) \times i = N \times \phi \tag{8}$$

And the motion electro-motive of the movable part can be represented as function of the movable-part velocity, the coil current, and the changing rate of coil inductance with respect to time:

$$e = vi\frac{dL(x)}{dx} = f_v(x,i) \tag{9}$$

Notice that flux linkage λ and motion voltage e , as seen in (8) and (9), are the function of the movable-part velocity and the coil current.

A. Closing phase

Differentiates (8) with time, and results in

$$\frac{d\lambda}{dt}=L\frac{di}{dt}+i\frac{dL}{dt} \tag{10}$$

Substitutes (9) and (10) into (7), we obtain

$$u(t)=ir+(L\frac{di}{dt}+i\frac{dL}{dt})+vi\frac{dL}{dx} \tag{11}$$

Apparently, the relationship between the applied coil voltage and the coil current is complex and non-linear during closing process. Generally, it is a very difficult problem for designer or engineer to precisely predict the dynamic behaviours under this operating condition.

B. Closed phase

Once when the working status of contactor has entered into the closed phase, the value of coil inductance becomes a constant value and the motion voltage is zero. No movement of the movable part occurs during this sub-phase, so that (9) and (10) are simplified and written as

$$\frac{d\lambda}{dt}=L\frac{di}{dt}, \qquad e=0 \tag{12}$$

Meanwhile, the electrical equation of contactor be also further simplified and given by the following form:

$$u(t)=ir+L\frac{di}{dt} \tag{13}$$

Clearly, (13) is a one order ordinary differential equation. We can now derive the solution to (13).

$$i(t)=\frac{u}{r}(1-e^{-\frac{t}{\tau}}) \tag{14}$$

Equation (14) means that the value of coil current will exponentially increase at first and become a constant value through about five times time constant, τ $(=L/r)$, later.

3.3 Mechanical Part

The mechanical part of device is consists of movable part, stationary electromagnet, return springs, and contacts' springs. In fact, the mechanism of contactor is really a mass-spring-damp system. As a consequence, the dynamic behaviours of the mechanical part can be represented by a second order ordinary differential equation as follows.

$$F_e=m\frac{d^2x}{dt^2}+B\frac{dx}{dt}+kx \tag{15}$$

Most of the time, the viscous coefficient in the mechanical part is small, therefore, it is assumed to be ignored here. At the same time, the total counter force of device is also defined as F_f. We will now reduce (15) to a simpler form.

$$F_e-F_f=m\frac{d^2x}{dt^2}=\Delta F \tag{16}$$

In case of the coil is energized by an external voltage, the expression of the magnetic force which acts on the movable part can be represented as follows:

$$F_e=\frac{1}{2}i^2\frac{dL(x)}{dx} \tag{17}$$

Generally speaking, most of the dynamic time of device, the movable part is situated at moving state during closing process. This means that the value of magnetic force sometimes below the value of springs' counter force is allowed.

4 Energy Analyses

When the contactor is voltage fed by an ac voltage source, the power energy is absorbed by the device for making the contacts close and preventing the contacts from dropping out. As mentioned above, there are three sub-phases are commonly included in a complete contactor's working process. The sub-phases of closing and closed are closely concerning with the mechanical motion. Especially, since the relationship of the dynamic parameters is complex and non-linear, it is very difficult to predict the contactor's dynamic behaviours in the closing process.

First of all, the expression of the coil applied voltage, as described in (7), is multiplied by coil current to each side, and then lead to following expression:

$$ui=i^2r+i\frac{d\lambda}{dt}+vi^2\frac{dL}{dx} \tag{18}$$

On substituting the representations of magnetic force F_e, spring load counter force F_f, and their difference ΔF, which are defined in (7), into (18), and then results in:

$$\begin{aligned} ui &= i^2r+i\frac{d\lambda}{dt}+2vF_e \\ &= i^2r+i\frac{d\lambda}{dt}+2v(F_f+\Delta F) \\ &= \underbrace{i^2r}_{1}+\underbrace{i\frac{d\lambda}{dt}}_{2}+\underbrace{2F_fv}_{3}+\underbrace{2\Delta Fv}_{4} \end{aligned} \tag{19}$$

The average power is the work done W divided by the time period and given by [1]:

$$P=\frac{W}{\Delta t} \tag{20}$$

where P is the average power. If the work is done by a very short time period, namely $\Delta t\to 0$, the power value acted on a contactor become an instantaneous power and the expression is given by the following form:

$$P = \lim_{\Delta t \to 0} \frac{W}{\Delta t} \tag{21}$$

Based on the work-energy theorem, the work done by the device is equal to its total input power energy. Equation (19) means that the input power of device is distributed to each subsystem. The total input power energy of contactor within a time period, ($t_0 \sim t_S$), can be computed by the following expression:

$$\begin{aligned} E &= \sum_{i=0}^{s} E(t_i) \\ &= \sum_{i=0}^{s} u(t_i) i(t_i) \Delta t \\ &= E_r + E_L + E_S + E_v, \quad \Delta t = t_i - t_{i-1} \end{aligned} \tag{22}$$

where the symbols are respectively defined as:

E_r : is the dissipated energy in the coil resistance, which is equal to $\sum_{i=0}^{s} i^2(t_i)\, r \Delta t$;

E_L : is the stored energy in coil inductance, which is equal to $\sum_{i=0}^{s} i(t_i) \frac{d\lambda}{dt} \Delta t$;

E_S : is the stored energy in the spring system, which is equal to $\sum_{i=0}^{s} 2F_f v(t_i) \Delta t$;

E_v : is the energy dissipation for moving movable part, which is equal to $\sum_{i=0}^{s} 2(\Delta F) v(t_i) \Delta t$;

E_e : is the total energy for acting on the movable part, which is equal to the partial-energy addition both E_S and E_v .

5 Laboratory Test

In this paper, the experimental contactor is manufactured by a native company, Shilin. The device is a tripolar contactor and its type is S-C21L. Applied coil voltage is an ac source, power line frequency is 60 Hz and its rated root-mean-square voltage is 220 V_{RMS} . Rated contact capacity is 5.5 KW, the number of coil turns is 3750, the coil resistance is 285 Ω , and the mass of the movable part is 0.115 Kg.

5.1 Establishing Simulation Model

The dynamic simulation model of contactor is established by means of the electrical circuit equation and mechanical motion equations. First of all, five individual simulation modules are established according to their governing equations. Next, these modules are combined with each other and results in a complete contactor model, as shown in Fig. 5.

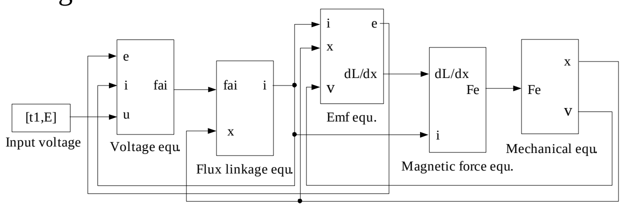
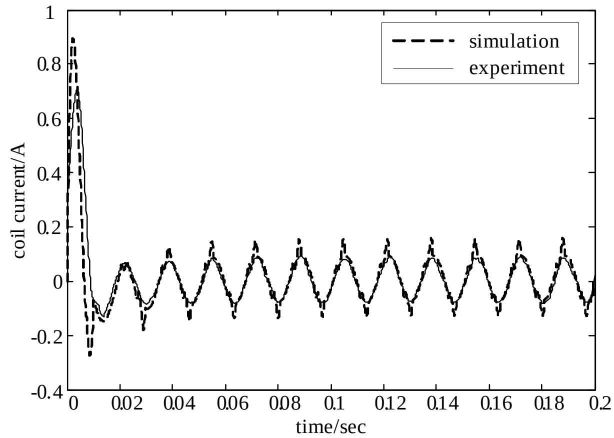
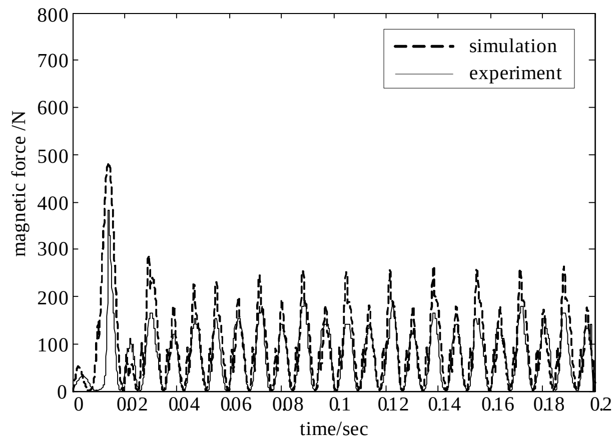


Fig. 5. Complete electromagnetic contactor model.

The comparison is essential to verify the correctness of the developed ac contactor model used in simulation. By using the simulation and experiment process, the parameters such as coil current, magnetic force, counter force and movable-part position, are obtained and compared. From Fig. 6(a) to Fig. 6(d), it is true that the simulation results are agree well with the experimental results.



(a)



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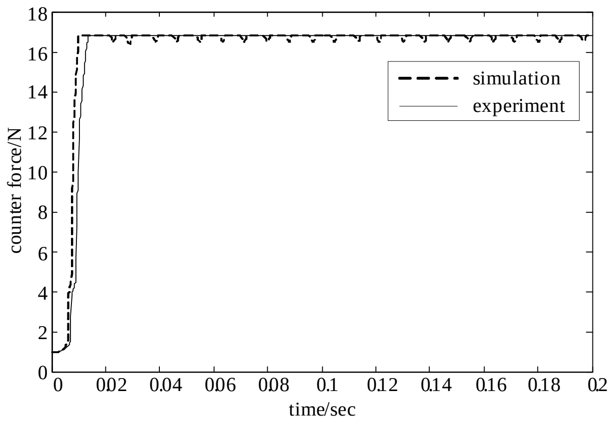

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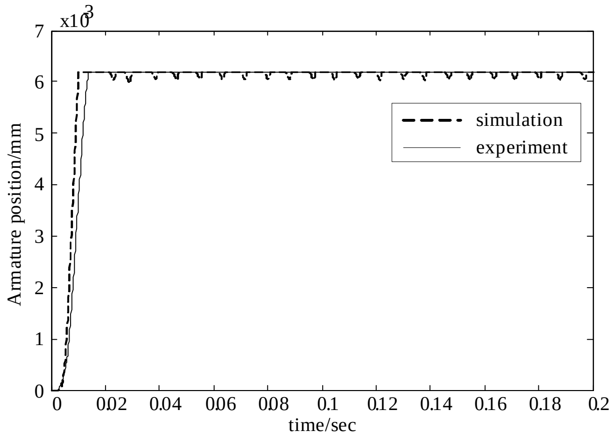


(d)

Fig. 6. Parameters comparison (a) coil current (b) magnetic force (c) counter force of spring (d) movable-part position.

5.2 Simulation Results

If the accumulated input power energy of contactor is able to be minimized at the end of closing phase, the impact of the movable-part kinetic energy on the contact bounce should be decreased. This means that movable contact and fixed contact are to be closed by using soft landing method. It is natural that the number of contact bounce should has been effectively controlled and reduced greatly.

5.2.1 Influence of the initial voltage phase upon the input power energy

It is known that contact bounce occurs when the contactor executes the closing operation. For exploring the relationship between the input power voltage and initial voltage phase (It is assumed that contactor is fed by a sinusoidal voltage), the simulations are carried out through a contactor model which is established by the dynamic simulation software package Matlab/Simulink. Fig. 7 shows the simulation results and reveals two important results: the first is the applied coil voltage with initial voltage phase is near 90 degree and 225 degree for every power line cycle, where appears low-value input power energy be absorbed by device. The second is the minimum input power energy appears one time for every cycle, namely 180 degree.

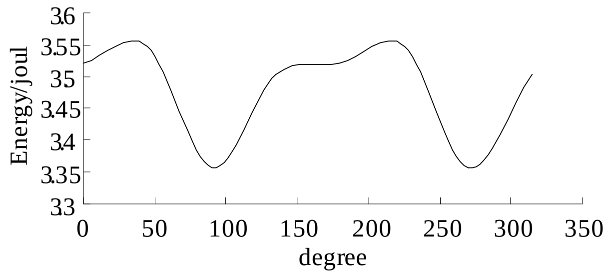
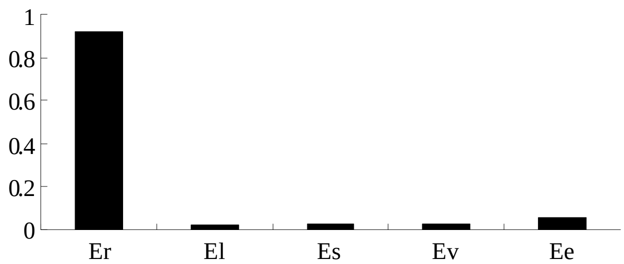


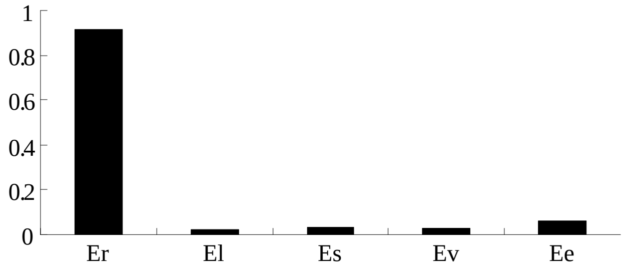
Fig. 7. Input power energy varies with initial voltage phase of applied coil voltage.

5.2.2 Energy distribution of each subsystem

The input power energy of contactor has been demonstrated that repeats every 180 degrees. Take the same coil voltage for different initial phase angle, for example 0, 45, 95 and 135 degrees, into consideration, the amount of dissipated energy is absorbed by each subsystem is calculated and their simulation results are plotted together for convenient comparison, as shown in Fig. 8.



(a)



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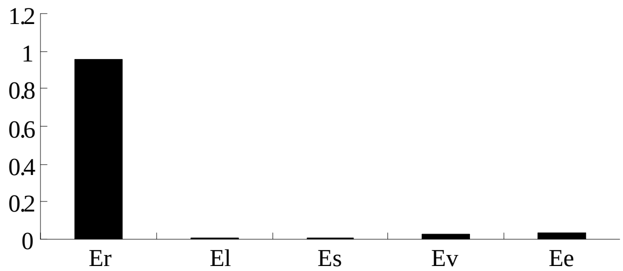

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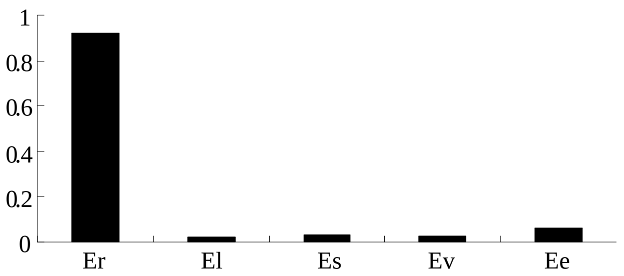


(d)

Fig. 8. Dissipated energy comparisons in each subsystem for the coil is energized by an ac source with initial voltage phase at (a) 0 degree (b) 45 degree (c) 95 degree (d) 135 degree.

As seen in Fig. 8, almost ninety percentages of the input power energy has been dissipated by the coil resistance; next about six percentage of input power energy is converted into the kinetic energy for movable-part motion. However, the energy dissipated in the spring's subsystem always is kept on a little volume during closing process. In particular, the stored spring energy E_S, at 95 degree is the smallest value among the periodic coil voltage. As a consequence, the necessary value of the magnetic force which acts on the movable part for closing contact and preventing the contacts from dropping out is small as well. This is the reason why the coil voltage of contactor is generally hope to be switched to a low dc voltage when the operating` state of contactor has transited from closing phase to closed phase.

5.3 Experimental Results

Fig. 9 shows that designed experimental rig for measuring the contact bounce during closing process. The coil is voltage fed through a sinusoidal source with the initial voltage phase 0 and 95 degrees respectively. By using digital scope, the contact bounce signals during closure time are obtained by measuring the voltage level across the resistance R. When the voltage level is high, it represents that the movable contact is closed with the fixed contact; on the contrarily, when the voltage level is low, it represents that contact status is kept on opening. As seen in Fig. 7, the dissipated energy for moving movable part is the smallest at 95 degree. Since the kinetic energy of movable part has the smallest value at impact time. Therefore, the collision speed of contacts and irons would be smaller than others time, hence the bounce of the contacts would be decreased significantly. Experimental results are displayed in Fig. 10. Clearly, the contact bounce of contactor has been reduced greatly as the coil is energized by the special initial phase angle of ac applied coil voltage.

The validation is done by means of the experimental results are agree with the results of simulation well. The experimental results also shows that proposed analyzing the energy dissipation in each subsystem for determining the best initial voltage phase of ac applied voltage is feasible.

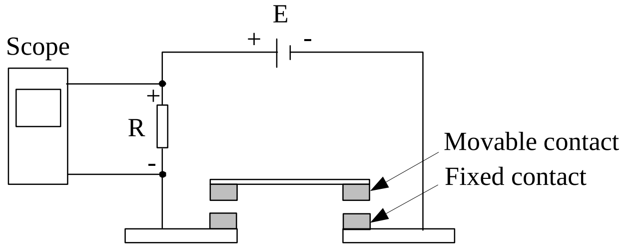
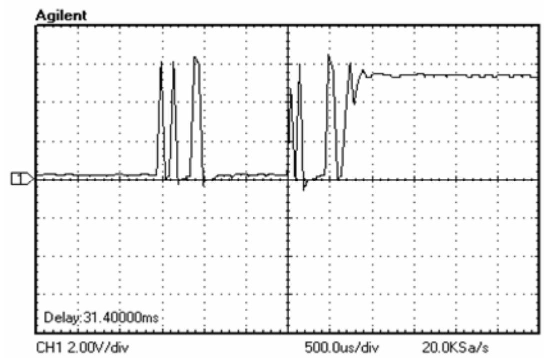
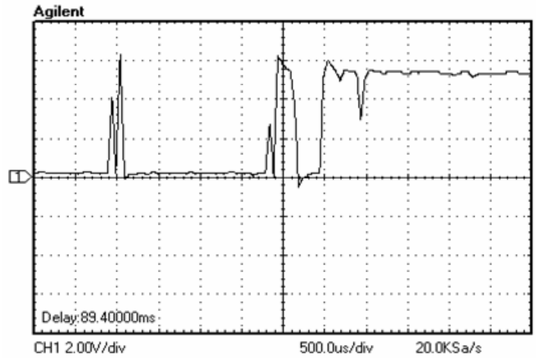


Fig. 9. Experimental rig for measuring the contact bounce during closing process.



(a)



(b)

Fig. 10. Comparison of the number of contact bounces for the initial voltage phase at (a) 0 degree (b) 95 degree.

6 Conclusion

Contactors are device which used in many control and power application fields. In closing process, there are a series of the contact bounce occur between contact pieces. In case of these contacts are used as the switch for turn on the heavy load. Consequently, the random and harmful arc occurs and damages to the contactor. In this paper, by analyzing the distribution of the input power energy at the end of closing process, we found an important fact that the more movable-part kinetic energy has, the more the number of contact bounce occurs. For the purpose of reducing the contact bounce, the best initial phase angle of ac voltage was found via energy-based analytical method. To properly select an initial phase angle of applied ac voltage based on minimizing movable-part kinetic energy during closing phase, a satisfactory closure result may be achieved. The effectiveness of our proposed approach was verified through simulation and experiment process. Moreover, the simulation and experimental results clearly depicted that the contact bounce of contactor was decreased greatly; hence the lifespan was increased and the operating reliability was improved as well.

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